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Investigations on the spatial resolution of autocollimator-based slope measuring profilers

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Abstract

During the last decade, autocollimator-based slope measuring profilers like the Nanometer Optical Component Measuring Machine (NOM) at BESSY-II have become standard instrumentation for the ultra-precise characterization of synchrotron optics with nanometer accuracy. Due to the increasing demand for highest accuracy, which can be provided by these profilers, further investigations are necessary to understand the performance of these instruments. Besides the achievable accuracy, it is of particular interest to characterize the possible spatial resolution of such instrumentation. The performance of the BESSY-NOM was characterized by means of sinusoidal and chirped surface profiles. A dedicated sample was prepared using the Atmospheric Plasma Jet Machining technology at the IOM - Leibniz-Institut für Oberflächenmodifizierung e.V.. We report on our tests on the NOM, the interferometer measurements done for comparison as well as the sample preparation.

Keywords: Synchrotron Optics, X-ray Optics, NOM, Metrology, LTP

1. Introduction

Autocollimator-based slope measuring profilers like the Nanometer Optical Component Measuring Machine (NOM) [1, 2] at BESSY-II have become standard instrumentation for the ultra-precise characterization of synchrotron optics with sub-nanometer accuracy [3]. Several synchrotron laboratories like DIAMOND (UK) [4], ALBA (Spain) [5] or the ALS at LBNL (USA) [6] operate these devices. Other labs like NSLS-II (USA), the APS (USA) [7] and SSRF (China) also intend to pursue the same path. The Physikalisch Technische Bundesanstalt (PTB) in Germany is even upgrading its ESAD system, another autocollimator-based instrument of highest accuracy [8, 9]. Past experience has shown that a careful characterization and calibration of slope measuring profilers is essential to achieve the accuracy requirements for the synchrotron optics of today [10, 11]. A further issue of discussion is the spatial resolution achievable by slope measuring deflectometry. In past publications it was proposed to perform investigations on this topic by use of dedicated test samples of periodic and chirped profiles [11, 12].

2. Sample design and preparation

The application of sinusoidal and chirped profiles for instrument characterization was discussed in previous publications [11, 12, 13]. Rose and coworkers [13] applied sinusoidal profiles of 2 mm period with a comparatively high amplitude of 800 nm and proposed chirped profiles of about 4.5 µm pv for the calibration of a measuring device for future work. However, the purpose of slope measurements in X-ray optics is to identify figure deviations in the range of only a few nanometer pv. Thus our intention was to prepare a sample with periodic and chirped profiles of 5 nm amplitude (after subtraction of background figure error). Atmospheric Plasma Jet Etching with a narrow beam size of 0.4 mm FWHM [14] was applied for deterministic local etching of shallow sinusoidal profiles with a nominal pv of 5 nm on a flat silicon disc. We realized a lateral period of 0.5, 1.0 and 2.0 mm for three profiles. Furthermore, a chirped profile was made with a spatial variation of 0.5 – 10.0 mm, described by the following equation:

$$y = A(\cos(2\pi p^{-1}x) + 1)), \qquad (1)$$

where A = 2.5 nm and the period $p = 0.3\ (1+x^{0.5})$. The sample is made on a super-polished single crystal Si-substrate of 100mm in diameter and 10mm thickness. The initial substrate flatness was measured with λ/20 peak to valley (λ=633 nm) and the micro-roughness was < 0.1 nm rms (measured by use of an interference microscope, magnification 20x and 50x). The set-up and an interferometric overview measurement of the sample are shown in Fig. 1. Fig. 2 depicts more detailed measurements for the 1 mm, 2 mm periodic and the chirped profiles. The droplet structure which occurs in the 2mm profile measurements, is caused by a nitrogen air blower contaminated by oil or grease. Small droplets mask the surface during plasma jet etching, partially resulting in a significant increase of surface roughness which is also found in the interference microscope measurements, see Fig. 3.

3. Performance tests by use of different diaphragm diameter

In the NOM and the ESAD systems, a diaphragm of circular geometry is used to define the diameter of the measurement beam of the autocollimator. Figure 4 shows the set-up for the NOM-autocollimator in a scanning “pentaprism like” configuration. The diaphragm-mechanism is linked to the scanning carriage of the NOM and is aligned with respect to the beam guiding 45° double mirror set-up. The diaphragm is positioned telecentrically to the autocollimator`s optical axis. It is placed at a short distance of three millimeters to the surface under test, see Fig. 4. A diameter of 2.5 mm is applied to the BESSY-NOM for standard measurements. In principle, a diameter of 2.0 mm can be applied for such a measurement. However, it is known that smaller aperture diameter result in diffraction as well as interference effects [15] and distorts the reticle image of the autocollimator detected on the CCD-sensor. Thus, a significantly higher level of noise is found on the measurement. The level of noise can be taken as a usable indication for an optimal diaphragm size and diaphragm alignment to the NOM. In case of concave curved optics (down to radii of R = 5 m), significantly smaller apertures with diameters down to 0.8 mm [11] were used. It is also known that other autocollimator based slope measuring profilers use larger beam diameters up to 5mm (e.g. at the ESAD-system of the PTB).

Several measurements with beam diameters of: 1.8, 2.0, 2.5, 3.0, 5.0 and partly with 10.0 mm along the different sections of the sample were performed to test the influence of the diaphragm diameter on the instrument performance in terms of spatial resolution. The measurements were performed in a step by step mode. An equidistant sample spacing of Δx = 0.2 mm was taken along the 1.0 mm and 2.0 mm period as well as on the chirped profile. The 0.5 mm period was measured with Δx = 0.05 mm sample spacing. Each measurement was performed in a forward backward mode (to suppress linear drift contributions on the error budget [16]) and consisted of ten scans in each direction finally averaged.

4. Discussion of measurement results

Figures 5, 6, 7 show the slope profiles and the corresponding height profiles measured on the 0.5, 1.0 and 2.0mm sinosoidal periods for different diaphragm sizes applied. The strong deviation between the 10 mm diaphragm measurement and smaller sizes in Fig. 6 results from a circle fit applied to the full measurement length including the edge zone of the 1 mm period section. A clear correlation between diaphragm size, beam diameter, and spatial resolution is found. For larger beam diameter ≥ 5mm a phase shift of half a period is observed in case of higher spatial frequencies. However, higher spatial frequency shape deviations are not resolved in terms of height. The measurements on the chirped profile confirm this performance observation, as shown in Fig. 8. The measurements on the chirped profile show the correlation between the beam diameter and the corresponding critical spatial frequency, seen as a shift in the recorded slope and height profiles at a certain profile position.

Higher spatial frequencies of 1.0 mm^{-1} or shorter can be detected with a larger beam diameter of 2.5 or 3 mm. However, they cannot be fully resolved in terms of height. It can be taken as an analogy to the decrease in contrast, known from e.g. X-ray microscopy [17] or Transmission Electron Microscopy (TEM) [18, 19], where techniques of contrast enhancement are applied to improve the image quality. Note: the knowledge of this characteristics in the performance of autocollimator-based slope measuring profilers is an important point to consider, e.g. when applying slope-measurement based mapping data to calculate the removal simulation for deterministic surface finishing applications like Ion Beam Figuring (IBF) [20, 21].

A further option to analyze the spatial resolving power for different diaphragm sizes is given by use of the power spectral density (PSD) function.

In X-ray optics, the quality of optical elements is described in terms of rms roughness for the high spatial frequency error part as well as the rms residual slope deviation for the long spatial frequency error, from 1 mm^{-1} to full aperture length [22, 23]. Since, the NOM is a direct slope measuring profiler we discuss the surface slope profiles in terms of power spectral density (PSD). Figure 9 depicts the PSD-distribution of the direct measured slope profiles shown in Fig 5a, 6a, 7a. These curves are directly gained by discrete Fourier transformation, see Refs: [24, 25]

$$P_{DFT}(f) = \Delta x \cdot \left| F\left[\sigma(x_n)\right]\right|^2 . \qquad (2)$$

With Δx for the measurement increment distributed along the measured trace $x_n = n * \Delta x$ and σ is the discrete surface slope distribution. The plotted PSD data in Figure 9 shows that identifying spatial periods of 1mm or less is possible by using an autocollimator in a diaphragm set-up as realized in the NOM-principle. However, taking the cut-off frequency as the criterion for the spatial resolution achieved, it is clearly demonstrated that a spatial resolution of about 1.7 mm is only achieved in case of the 2.5 mm standard diaphragm size (see Fig. 10 for the surface slope PSD on the chirped section). A higher spatial resolution of about 1.5 mm is achieved for 1.8 mm diaphragm diameter. Table 1 shows the achieved spatial resolution for different diaphragm size used for the chirped profile measurements. It is also noted here that a higher level of noise is found on the 1.8 mm (200 nrad rms) and 2.0 mm (100 nrad rms) diaphragm measurements, compared to the 2.5 and 3.0mm diaphragm measurements (30 nrad rms each). We have chosen the 95% rms standard deviation agreement of the 20 averaged forward and backward scanned profiles as a criterion for the noise.

Diaphragm diameter [mm]	Cut-off frequency [mm^{-1}]	Corresponding spatial resolution [mm]
1.8	0.65	1.50
2.0	0.64	1.55
2.5	0.60	1.70
3.0	0.56	2.00
5.0	0.29	3.50
10.0	0.13	7.70

Table 1 diaphragm diameter and corresponding cut-off frequency at the BESSY-NOM

4. Concluding remarks and outlook

The performance of autocollimator based slope measuring profilers, based on the ELCOMAT 3000/8, is significantly influenced by the diaphragm size applied to shape the measurement beam. Smaller beam sizes allow resolving higher spatial frequency periods and have a positive impact on the achievable height resolution. In view of the experiences on instrument calibration for different diaphragm sizes, discussed in previous publications [11] and the results of the tests discussed here, a beam diameter of 2.5 mm can be considered as an optimal size to be applied at autocollimator based slope measuring profilers like the NOM. Significantly larger beam diameters (≥5 mm) cause a position shift of higher spatial frequency periods to be found on the measured sample trace and have limitations with regard to the achievable spatial resolution. Since the NOM-autocollimator is calibrated for small diaphragm sizes like 2.5 mm, the instrument calibration is not valid for larger diaphragm sizes like 5 or 10 mm.

The application of periodic and chirped profiles, shown here can be utilized for all types of slope measuring profilers, like the NOM, ESAD or the LTP. In the future, it is planned to perform an instrument characterization for a new NOM-LTP head still under commissioning. Further investigations are proposed to be performed on significantly curved samples (R = 10 m) with dedicated periodic and chirped profiles. In addition, the performance of alternative geometries e.g. squared shapes to be used as diaphragm will be the subject of upcoming work.

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Figure

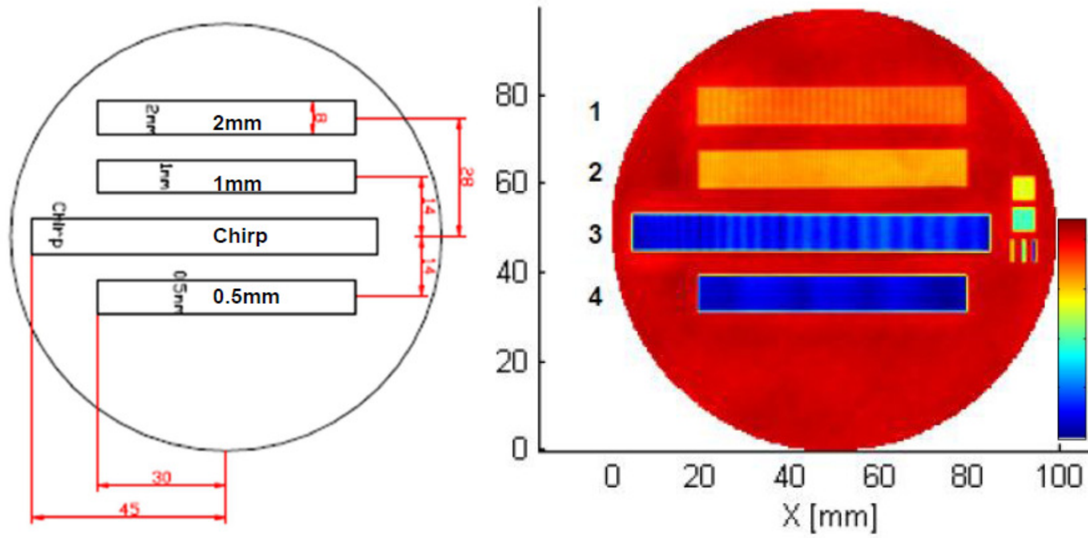

Figure 1: Sample set-up and interferometric measurement of the sample state.

Figure

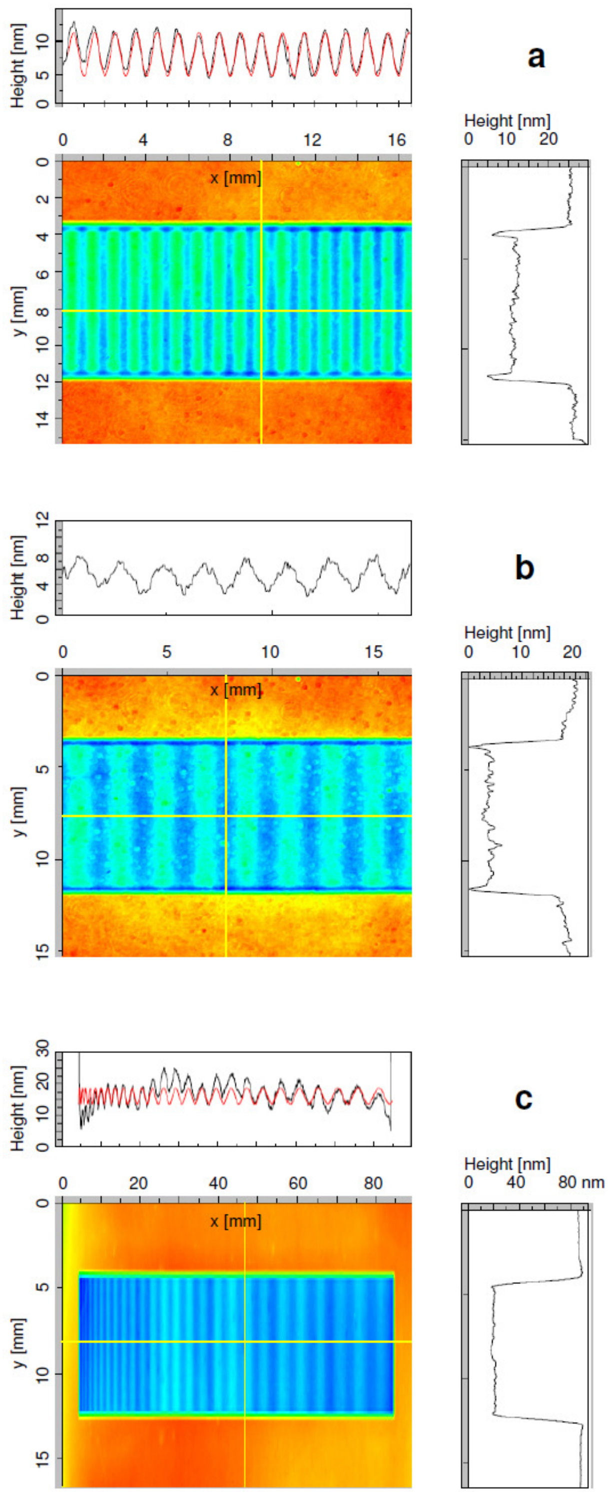

Figure 2: Interferometric measurements and cross sections for **a:** 1 mm, **b:** 2 mm and **c:** chirped sinusoidal structures

Figure

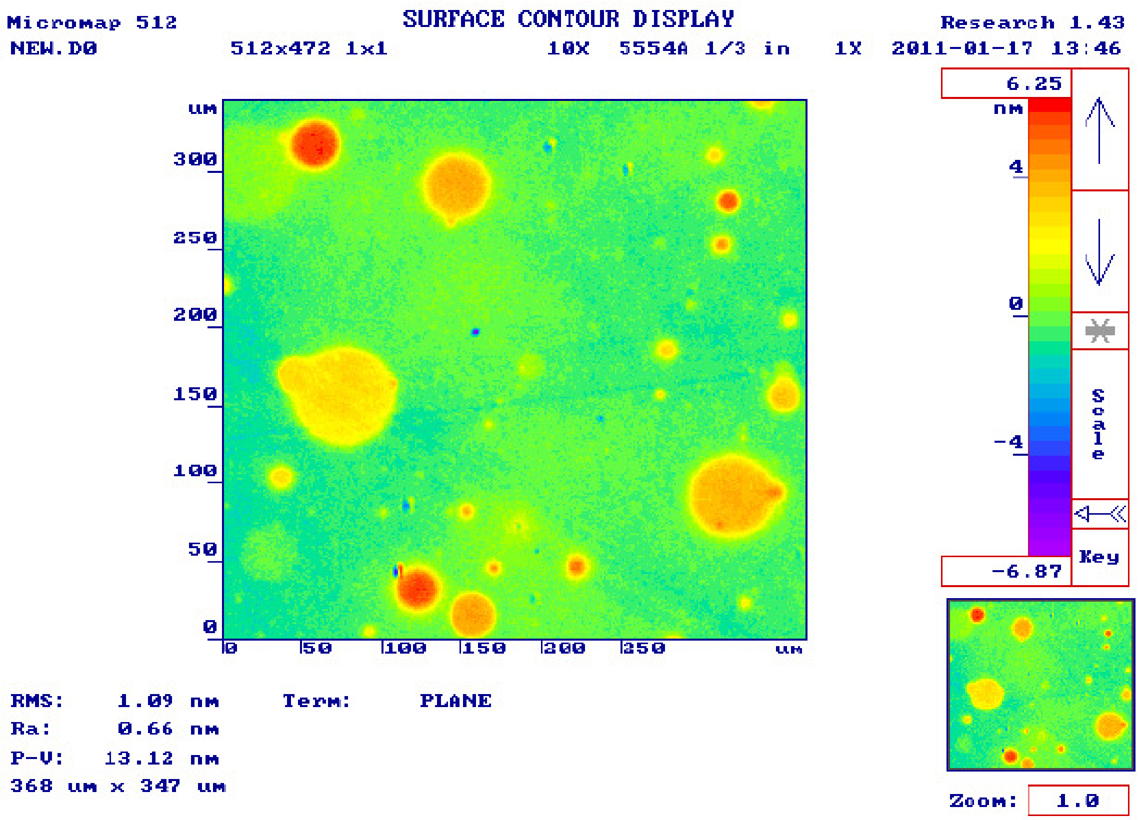

Figure 3: Surface roughness after etching the 2 mm period stripe. Circular structures are due to droplets from oil contaminated nitrogen blower which acts as a mask during plasma etching

Figure

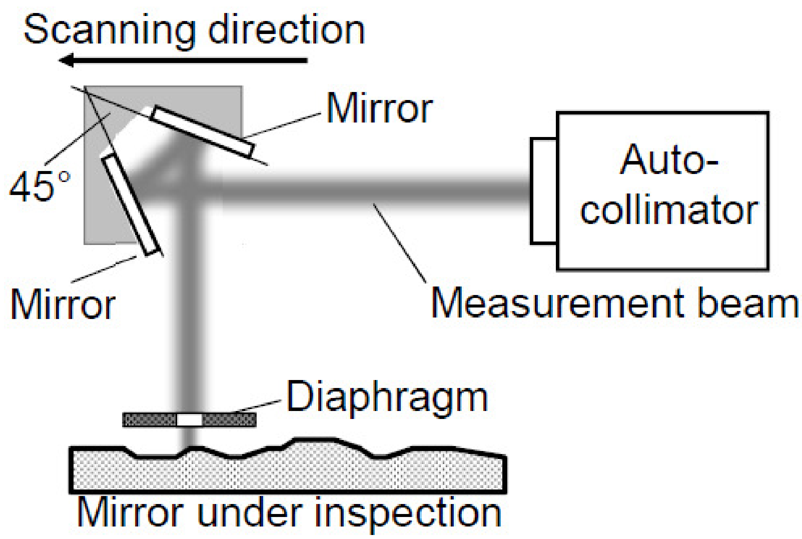

Figure 4. Principle optical set-up of an autocollimator based slope measuring profiler.

Figure

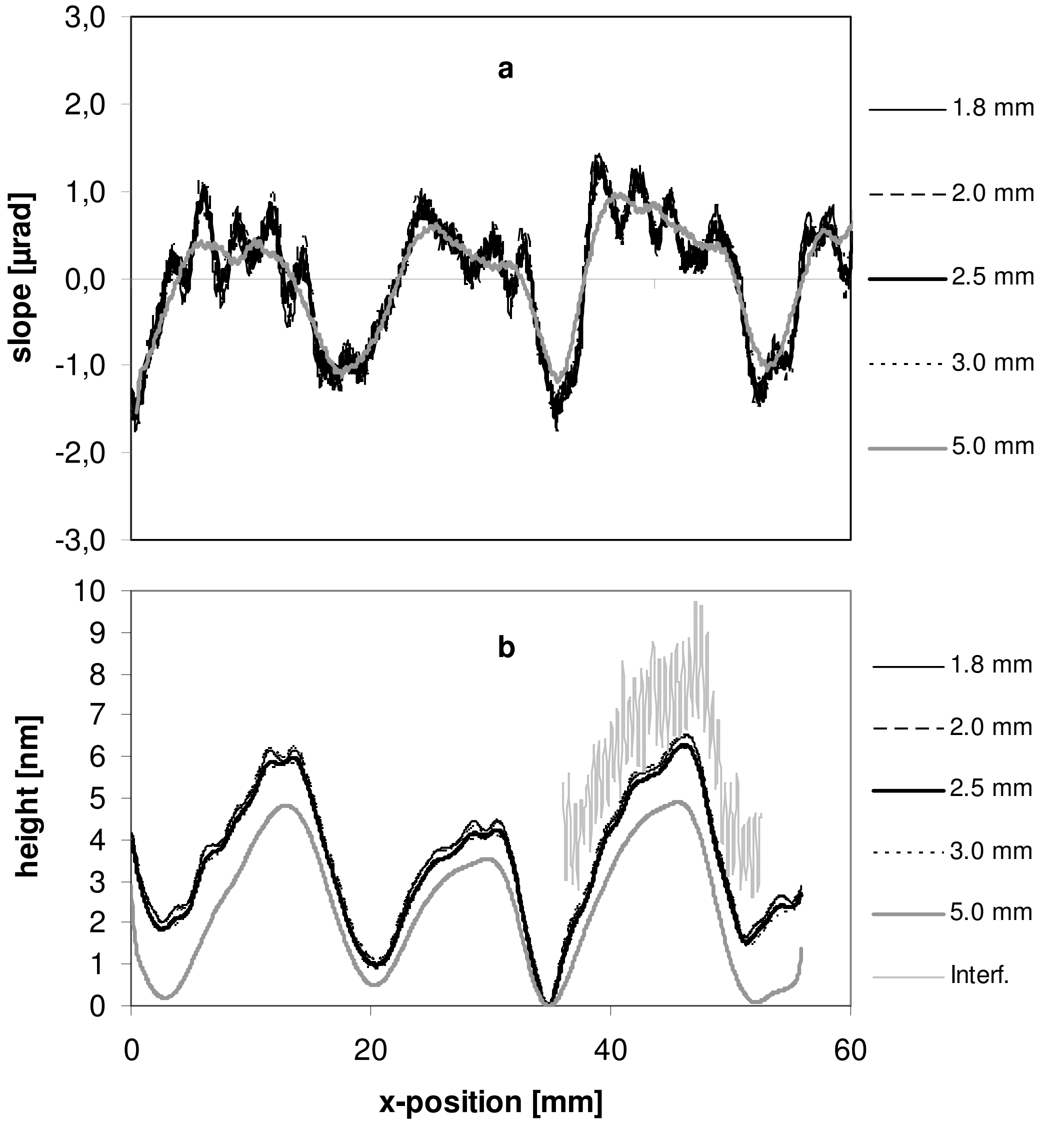

Figure 5. Profiles of a: residual slope and b: corresponding height achieved by use of different diaphragm size on a 0.5 mm period sinusoidal profile. For comparison a section of an interferometer measurement is added to the height profiles. The resolution of the interferometer measurement is about 35 µm.

Figure

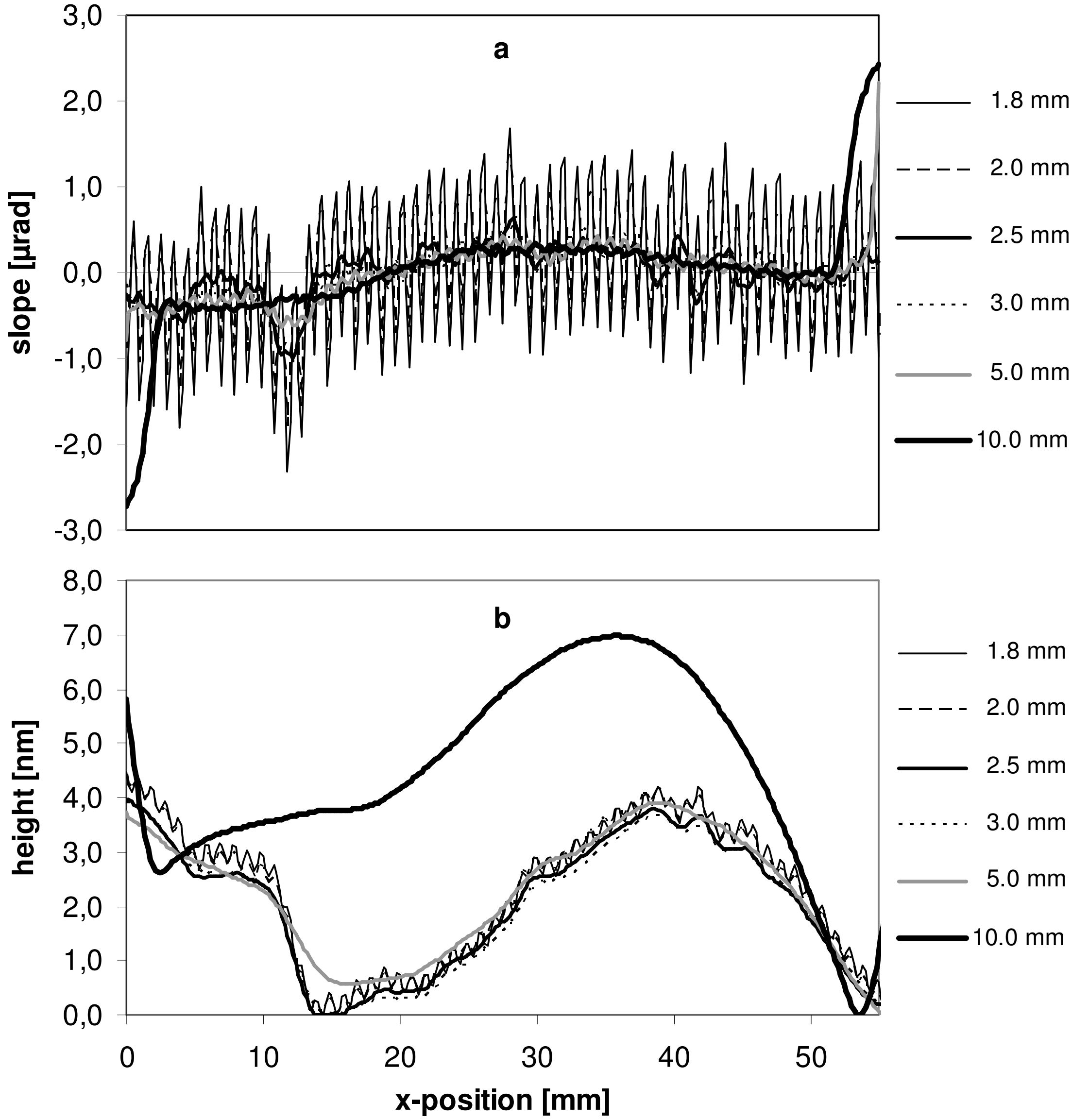

Figure 6. Profiles of a: residual slope and b: corresponding height achieved by use of different diaphragm size on a 1.0 mm period sinusoidal profile.

Figure

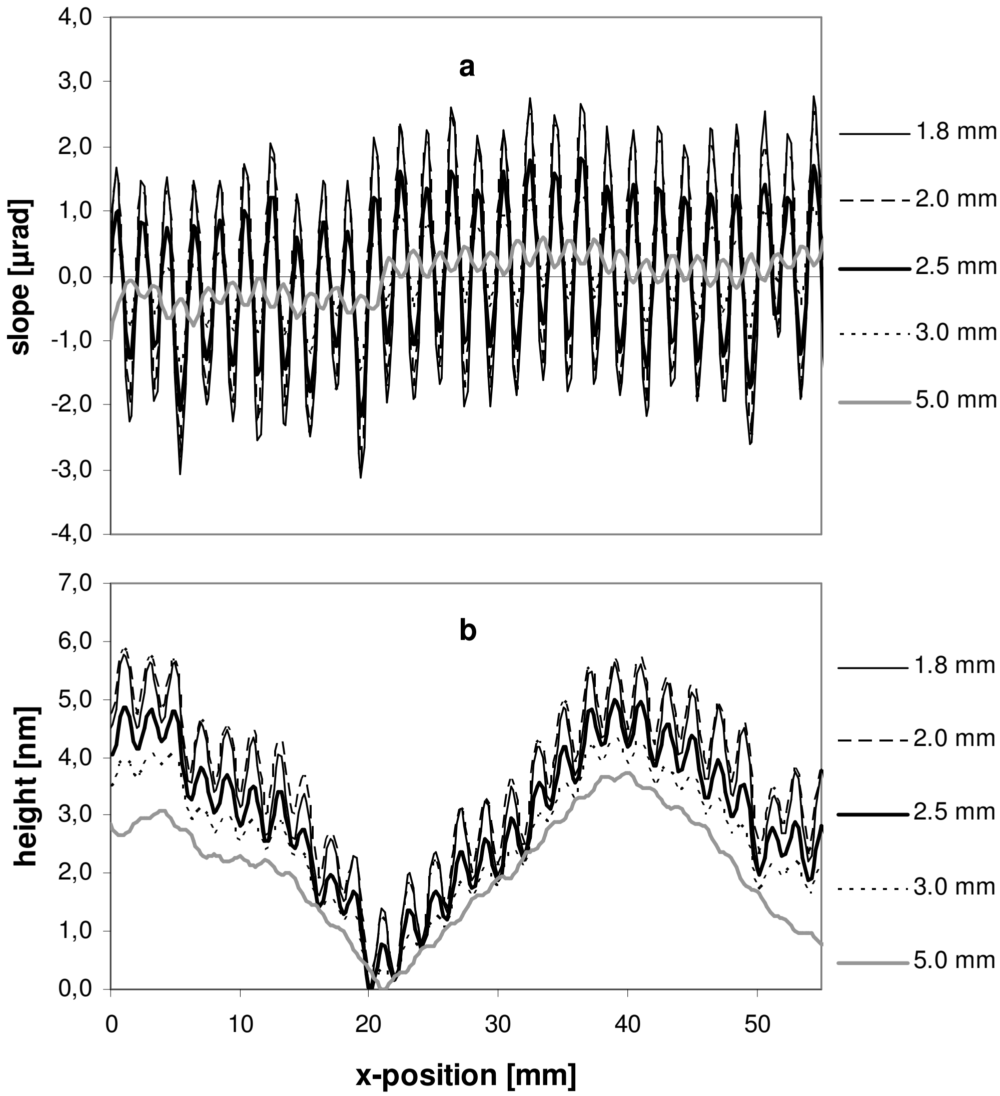

Figure 7. Profiles of a: residual slope and b: corresponding height achieved by use of different diaphragm size on a 2.0 mm period sinusoidal profile.

Figure

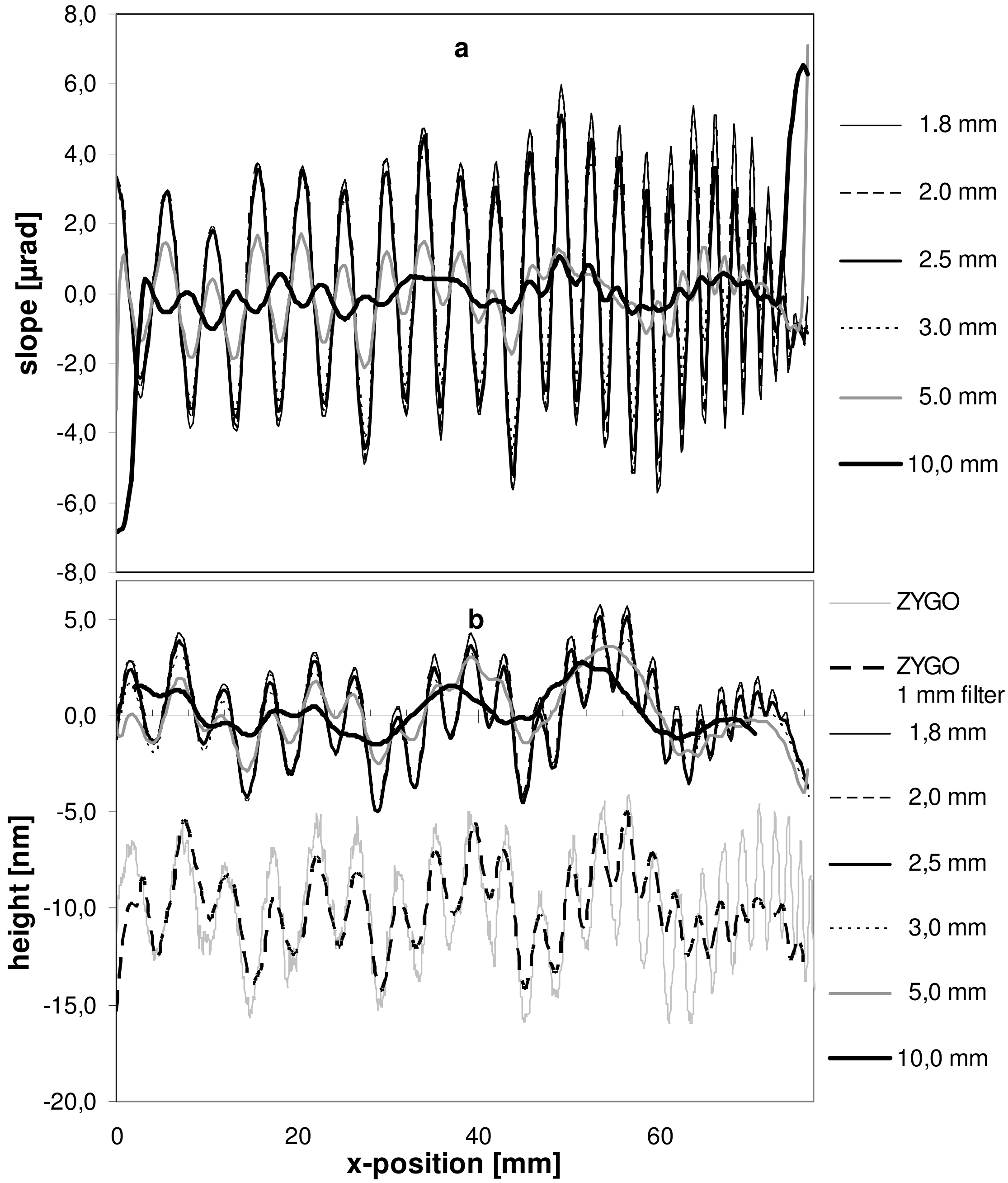

Figure 8. Chirped surface profile as measured by use of different diaphragm size on the NOM and by use a Fizeau Interferometer [filtered (1 mm) and unfiltered data], **a:** residual surface slope and **b:** corresponding residual height profile. A shift was subtracted from the two ZYGO interferometric measurements for better visualization.

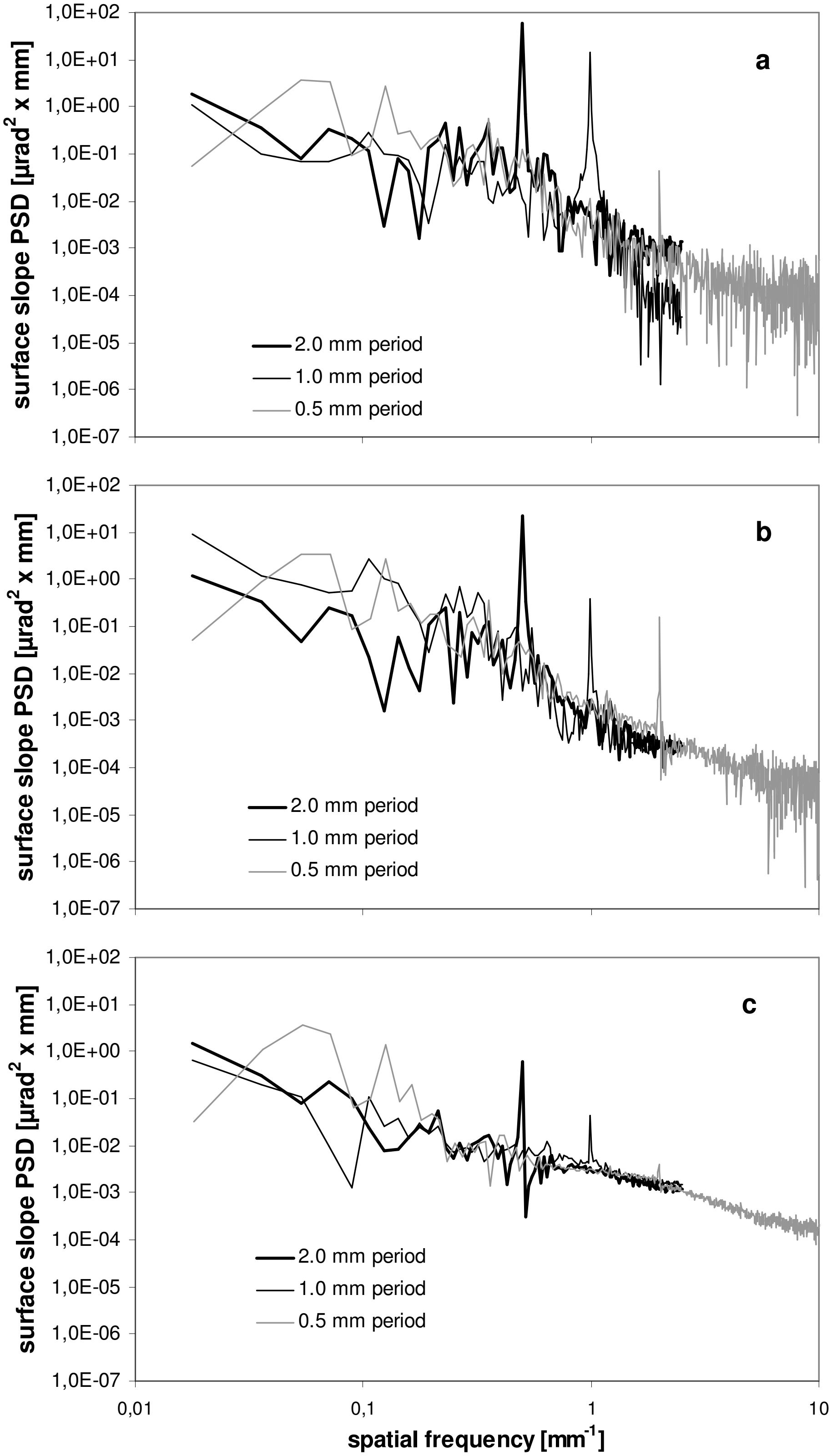

Figure 9. Curves of surface slope PSD as measured on 2.0, 1.0 and 0.5 mm sinusoidal periods by use of different diaphragm size, **a:** 1.8 mm, **b:** 2.5 mm, **c:** 5.0 mm.

Figure

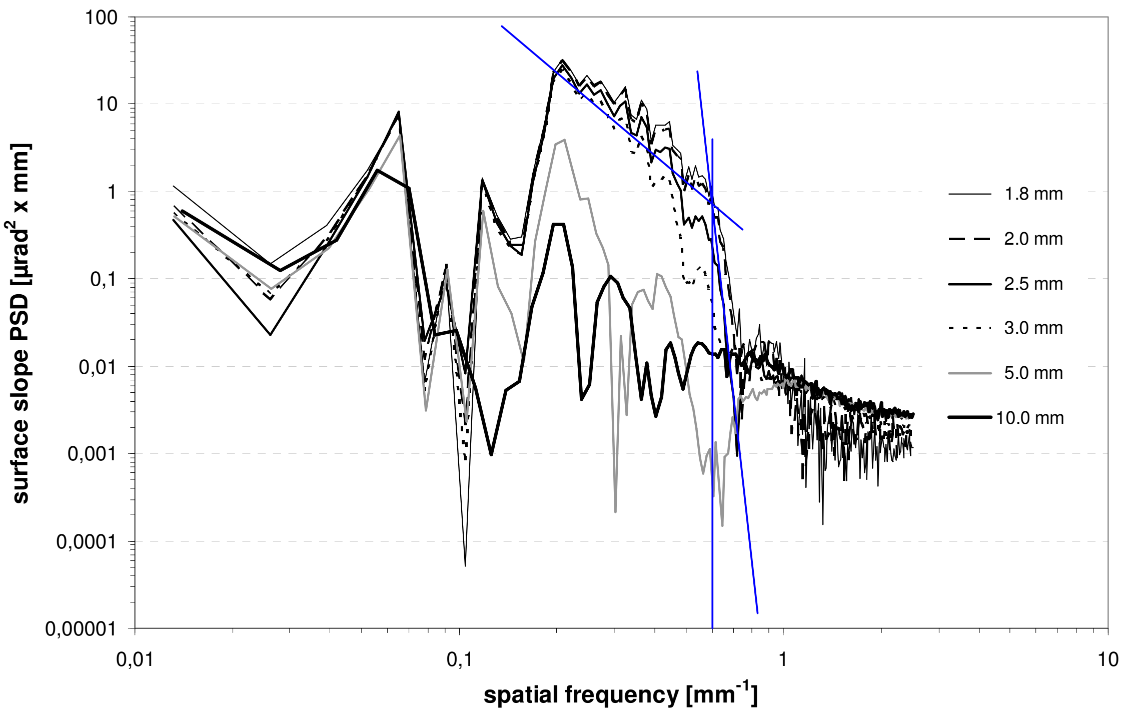

Figure 10. Curves of surface slope PSD as measured on a chirped profile by use of different diaphragm size. The cut-off frequency for the 2.5 mm diaphragm of 0.6 mm^{-1} is marked by the vertical blue line

Table

Diaphragm diameter [mm]	Cut-off frequency mm^{-1}	Corresponding spatial resolution [mm]
1.8	0.65	1.50
2.0	0.64	1.55
2.5	0.60	1.70
3.0	0.56	2.00
5.0	0.29	3.50
10.0	0.13	7.70

Table 1 Diaphragm diameter and corresponding cut-off frequency at the BESSY-NOM.